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Qualification Testing of a Diode-Laser Transmitter for Free-Space Coherent Communications

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FOR THE COMMANDER

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QUALIFICATION TESTING OF A DIODE-LASER TRANSMITTER FOR FREE-SPACE COHERENT COMMUNICATIONS

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ABSTRACT

A diode-laser transmitter designed for space-based coherent communications has been successfully space qualified. Environmental testing, which consisted of random vibration at levels up to 16.2 *g* rms and thermal cycling over the range of −30 to 66°C, caused no significant degradation in the performance of the transmitter. Principal design issues and the qualification process of subassemblies and the complete transmitter are described.

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1. INTRODUCTION

Optical communications between satellites offer many advantages over conventional radio frequency systems for certain applications. The very narrow beams are resistant to jamming and interception; very high data rate systems are possible even with low-power lasers and small apertures. The potential of such a system has led many organizations to propose and develop the technologies that will be necessary for such systems [1-4].

MIT Lincoln Laboratory is developing a heterodyne, 4-ary, frequency-shift-keyed (FSK) intersatellite communications system to operate at 220 Mb/s using directly modulated GaAlAs diode lasers operating at wavelengths near 0.86 µm. As has been previously reported [5,6], the Laser Intersatellite Transmission Experiment (LITE) flight package includes a moderate-sized optical unit that contains a 20-cm aperture telescope; beam-pointing, acquisition, and tracking hardware; and beam diagnostics equipment [7]. This optomechanical subsystem (OMS) was designed to be mounted on a nadir-facing panel of a geosynchronous satellite for communication with other geosynchronous or low-earth-orbit satellites.

A key component in such a system is a rugged transmitter that is capable of operating reliably in the harsh environment of space. It must be able to tolerate severe vibrational, acoustic, thermal, and radiation stresses. A transmitter system has been designed [8] and constructed to meet these requirements. It includes four redundant diode-laser assemblies, conditioning optics, and part of a temperature controller. Achieving and maintaining the necessary high wavefront quality and precise internal beam pointing requires accurate placement and good stability of the critical optical components. The results are presented from the qualification process to which the LITE laser transmitter assembly was subjected.

2. SOURCE DESCRIPTION

The transmitter contains four redundant source assemblies [9] as shown in Figure 1. Each source assembly (see Figure 2) includes a Hitachi CSP 30-mW GaAlAs diode laser, a four-element collimator lens assembly, and a titanium support structure containing a small electronics compartment. A heater element is sandwiched between the diode mounting plate and the heater block and is used in conjunction with a thermistor mounted next to the laser to maintain the operating temperature of the laser with a precision of 0.001°C. The output from the source assembly is a 27-mW, 5 × 12-mm elliptical Gaussian beam. Typical wavefront quality is λ/25 to λ/40 rms. The source assembly allows direct frequency modulation of the laser with an RF bandwidth of 1 GHz (see Figure 3).

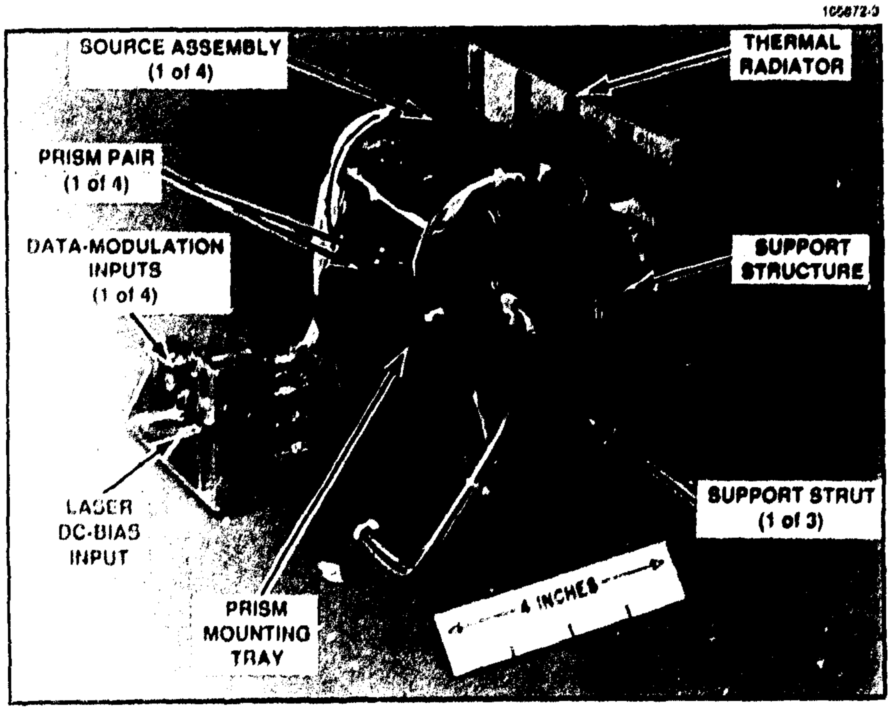

Figure 1. Transmitter assembly with a mass of 1.96 kg including an environmental cover, which is not shown.

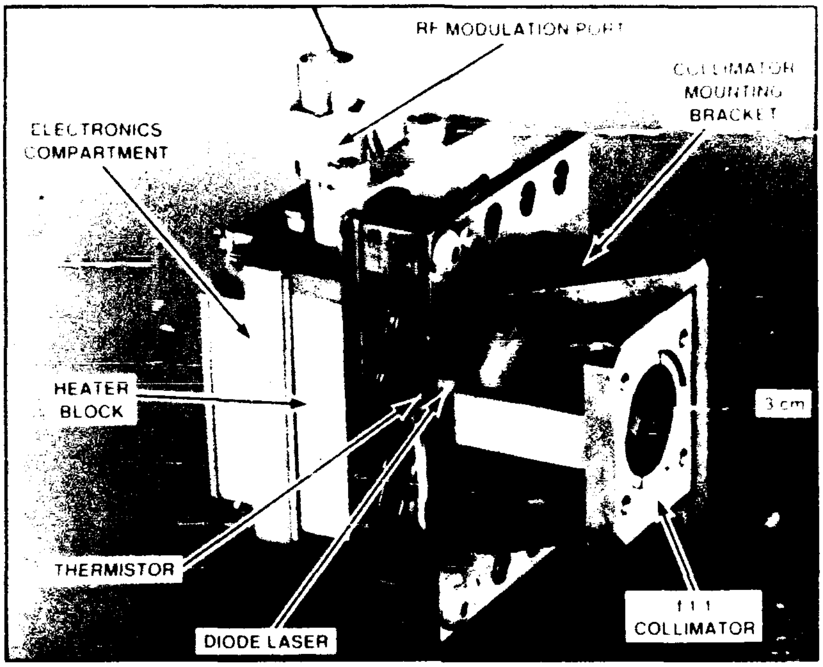

Figure 2. The source assembly with a mass of 160 g.

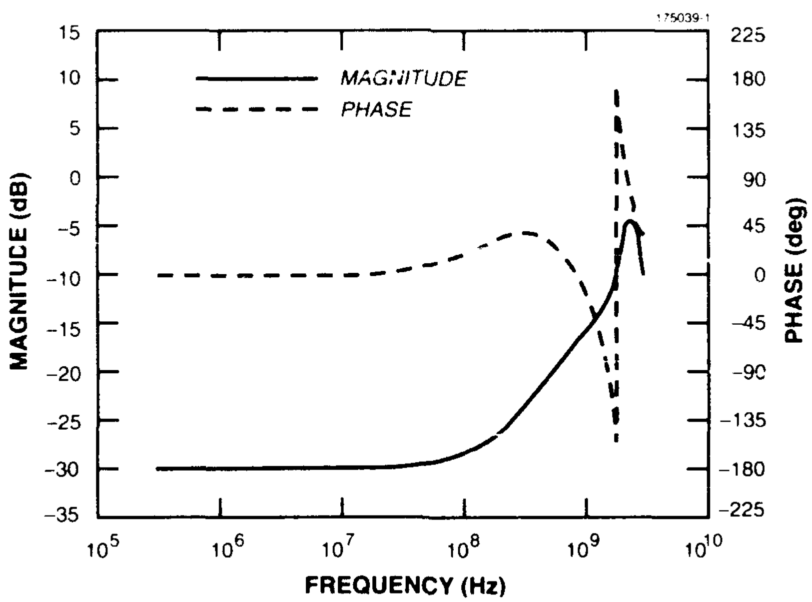

Figure 3. Measured power return loss into the data modulation port of the source assembly at 50 Ω. A return loss of 15 dB at 1 GHz is satisfactory for the highest required modulation rate of 110 megasymbols per second.

3. TRANSMITTER DESCRIPTION

The transmitter assembly contains four source assemblies that are supported by a titanium structure consisting of the housing, the support struts, and the prism mounting tray (Figure 4). Two sources are affixed to the structure and two below, with each beam directed towards its own fold mirror. The fold mirror directs the beam to an anamorphic prism pair, which circularizes the beam and points it to the beam intersection point located outside the transmitter. A two-axis, servo-driven fold mirror located at this point directs the active beam to the proper OMS beam path and corrects angular drift of the transmitter beam.

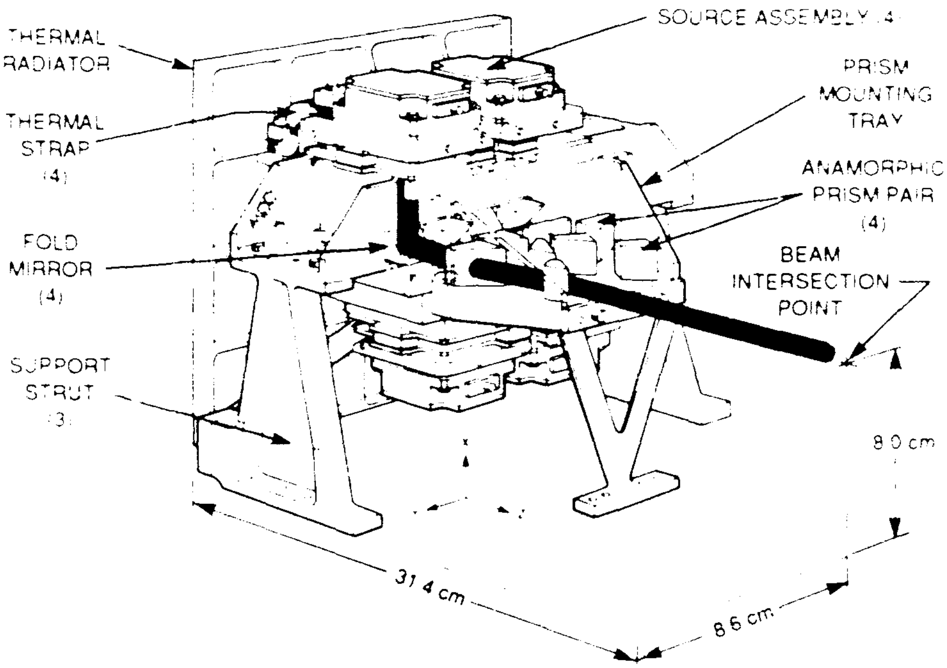

Figure 4. Transmitter assembly. A two-axis, servo-driven fold mirror located at the beam intersection point directs the active beam to the appropriate path.

The transmitter design must allow the sources to be operated anywhere in the 10 to 30°C range so that the laser can operate at the desired wavelength. To achieve this goal, the support struts were designed to provide high thermal isolation and a transmitter that is rigidly attached to the OMS. Waste heat is rejected by the thermal radiator, which is attached to the sources by flexible thermal straps.

Not shown is the protective cover, which supports a multilayer thermal blanket that covers the entire assembly.

The interfaces between components received a great deal of attention to ensure stability. The design minimizes the number of interfaces to limit potential failure sites. Where interfaces were necessary, the coefficients of thermal expansion of the two components were the same, or flexural mounting techniques were employed to accommodate the mismatch. Finally, critical bolted interfaces were also pinned to prevent lateral movements. For those locations where it would be difficult to install pins after final alignment, oversized holes were used on one side of the interface, and the annulus between the pin and the oversized hole was filled with a rigid epoxy after final positioning.

Maintaining low stress levels throughout the assembly also contributes to stability. An effective means to this end is to keep the structural resonant frequencies well above the disturbance frequencies. For the transmitter, the first modal frequency (390 Hz) is more than twice the peak disturbance frequency, and the remaining modal frequencies are more than three times the peak disturbance frequency. To achieve these high frequencies, transmitter mass must be kept low, providing the secondary benefit of reducing the loads proportionally. The peak 3σ stress within the titanium structure during random vibration testing was calculated to be 32 kpsi, less than one-half the expected microcreep strength [10].

4. OPTOMECHANICAL REQUIREMENTS

The relatively low optical power available from semiconductor lasers, along with the requirement for high data rates, dictates that the optical link must have minimal losses. Losses stemming from the transmitter may include truncation of the beam, imperfect wavefront quality, or beam attenuation through its optical train.

Truncation losses induced by beam walk are caused by imperfect alignment within the optical train. This misalignment may result from residual assembly errors, thermal distortions of the structure, or shifts in position of critical components due to launch and deployment loadings. In the optical design of the LITE system, a 100-μm walk of the transmitter beam (at the beam intersection point) would add 0.13 dB to the system loss.

Wavefront errors lead to a growth in beam size that can reduce the power incident on the receiver. Our budgeted wavefront error of $\lambda/20$ rms is expected to yield a maximum loss of 0.43 dB [11].

Many fabrication and alignment details can have an impact on transmitter wavefront quality and beam pointing. The most demanding tolerance is in the alignment of the diode laser to the collimator focal point. The collimator must be focused to within 0.7 μm to yield the budgeted transmitter wavefront quality ($\lambda/20$ rms) and be radially stable to within 1 μm to limit beam walk at the beam intersection point.

Transmission losses can occur due to absorption within the optical elements or from imperfect antireflection (AR) or high-reflection (HR) coatings. Each of the AR coatings within the transmitter has a reflectance less than 0.007, while the HR mirror coating provides a reflectance of better than 0.99. The Schott SF6-G5 glass used for the collimator and prisms has a low absorptivity at the operating wavelength and is resistant to radiation darkening. The resulting transmission loss, including collimator aperture truncation, is typically less than 0.8 dB.

5. QUALIFICATION TESTING STRATEGY

Of all the tests to which the transmitter may be subjected during qualification testing, thermal cycling and random vibration exposure pose the most severe loading. Acoustic excitation would not effectively couple into the transmitter, which is small compared with acoustic wavelengths. Sine sweep requirements are limited to 35 Hz, which is an order of magnitude below the first transmitter structural resonance. Shock loadings would be attenuated by the OMS support structure. The tests described are those that realistically might cause a failure. Remaining tests would be imposed after the transmitter had been integrated into the OMS, which would then be subjected to the full battery of tests as a complete module.

The vibration test levels for the transmitter were determined by finding the response of an OMS finite element model to the expected spacecraft random vibrations. Figure 5 shows the random vibration power spectral density (PSD) that was applied to the base of the OMS finite element model, as well as the response at the transmitter mounting location. The OMS support structure was designed to provide significant attenuation above 200 Hz.

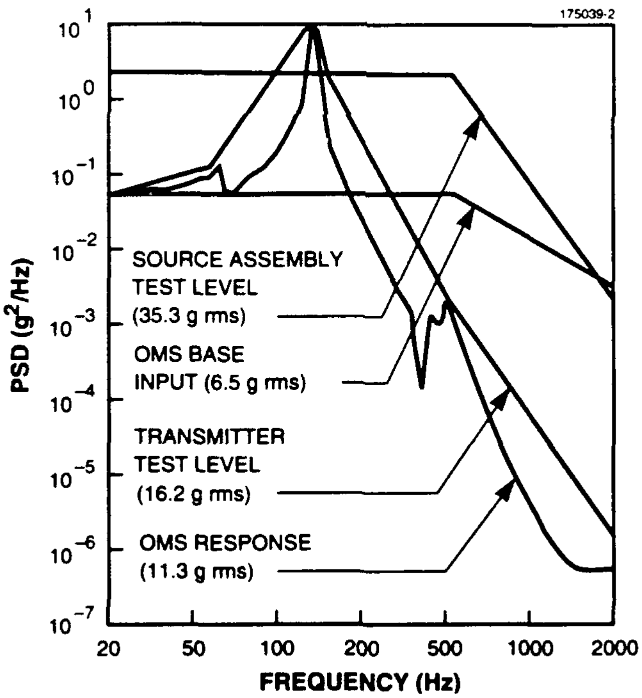

Figure 5. Random vibration PSD for the base of the OMS and the transmitter mounting location. Test levels for the transmitter and a source assembly are also shown.

The OMS response at the transmitter mounting location was then enveloped to give the test specification used for qualification testing of the transmitter as a subassembly. This banded response accounts for uncertainties in the model and establishes a test that will verify that the transmitter is capable of withstanding at least 1.5 times the loads expected during subsequent tests.

The first source assembly and several other components were available for testing well before the response of the OMS was known and before the test levels had been established. Figure 5 also shows the broadband test spectrum that was used during early testing of these components to establish their suitability for use in the transmitter. All the PSDs shown in Figure 5 are for the x-direction; similar curves were generated and used for the y and z axes.

Thermal cycling also imposes potentially damaging stresses because of the expected large excursions. The transmitter has a survival mode of operation that maintains the temperature at a minimum of −20°C. Conditions during launch and transfer orbit may allow the temperature to reach 50°C. To ensure some margin, the transmitter was thermally cycled between −30 and 66°C.

6. BEAM ALIGNMENT DEVICE

An important criterion for evaluating the performance of the transmitter is the location of the output beams. Figure 6 shows the beam alignment device that was constructed to measure the beam locations. It consists of a large-area quadrant detector mounted to a pair of motorized stages that provide *x-y* travel with a resolution of 0.1 μm. During qualification testing the transmitter remained secured to the transmitter mounting plate, which acted as a surrogate OMS bench. This mounting plate allowed repeatable placement on the beam alignment device by means of three half-sphere balls on the bottom surface that mated with V grooves in the beam alignment device base plate. Measurements of the beam locations were made by moving the quadrant detector until a null reading was achieved and then reading from the position stages, the incremental move from the ideal position. With careful technique, measurement errors were limited to less than 10 μm.

In addition to its function in qualification testing, the beam alignment device was used during the initial alignment of the transmitter. The first alignment yielded beam positions centered within 130 μm of the desired beam intersection point. Subsequent alignments have shown that the beams can be centered within 25 μm of this target.

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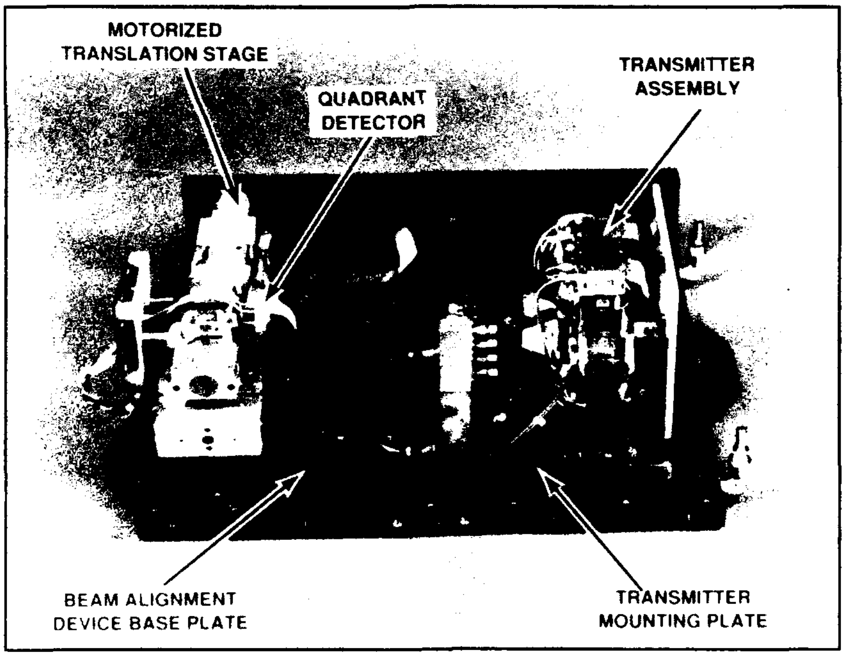

Figure 6. Beam alignment device that utilizes a quadrant detector to locate the beam centroid precisely.

7. QUALIFICATION OF SUBASSEMBLIES AND PROCESSES

Before the detailed design of the transmitter was started, critical components and techniques that had not previously been qualified were thoroughly tested. The components tested included the diode laser, the collimator, and a complete source assembly. The process for bonding flat optics to a metallic surface was also qualified. This preliminary testing helped to ensure a successful transmitter design.

Critical component testing included thermal cycling and exposure to high levels of broadband random vibration. Four diode lasers and one collimator were subjected to random vibration for 2 min in each of three axes at levels up to 49 *g* rms and six temperature cycles over a –20 to 66°C range. In addition, four unpowered lasers were subjected to 1 Mrad of ionizing radiation from a 1.5-MeV electron beam source. All tests were passed without detected change in characteristics.

The fold mirrors and anamorphic prisms within the transmitter are secured with adhesive. While the loading of these bond joints is not severe, the bonds must be very stable to prevent beam walk. To test the bond stability, the position of sample prisms was measured by autocollimating directly off a finished surface and by measuring the deviation of a reference beam that passed through the prism. Measurements were made before and after each exposure to environmental testing. No significant movement of these optics was observed.

A complete source assembly was also subjected to environmental testing with characterization before and after exposure. Particular attention was given to beam pointing and wavefront quality because these attributes are quite sensitive to small mechanical displacements or distortions. The source assembly survived random vibration (up to 35 *g* rms) and thermal cycle testing (–30 to 66°C) without significant change in either beam-pointing or wavefront quality. Figure 7 shows the change in wavefront profiles as a result of random vibration testing at the 15.2 *g* rms level. Two interferometric profiles were obtained: one before the vibration testing and one after. The data were then subtracted point by point over the aperture. A flat plateau would represent no change in the wavefronts; the change shown is less than $\lambda/150$ rms.

The source assembly was tested for wavefront quality over a wide temperature range to verify the accuracy of its athermal focal design, which is necessary because the source assembly temperature that yields the correct wavelength can vary as the laser ages. Figure 8 shows the results of these measurements. The wavefront quality for the source, a fold mirror and an anamorphic prism pair, was better than the goal of $\lambda/20$ rms throughout the range tested. The small variation in wavefront quality with temperature is thought to be primarily due to chromatic aberration caused by variations in the laser operating wavelength. In actual operation, the temperature would be selected to achieve a constant wavelength.

For a coherent communications link, transmitter frequency stability is important. Optical frequency drift of the source assembly was measured to be less than 10 MHz over a 1-min interval, which has been shown to allow a heterodyne receiver to acquire and track the signal readily. Since the thermal control loop crossover frequency is 0.5 Hz, it should be able to track out expected on-orbit thermal disturbances.

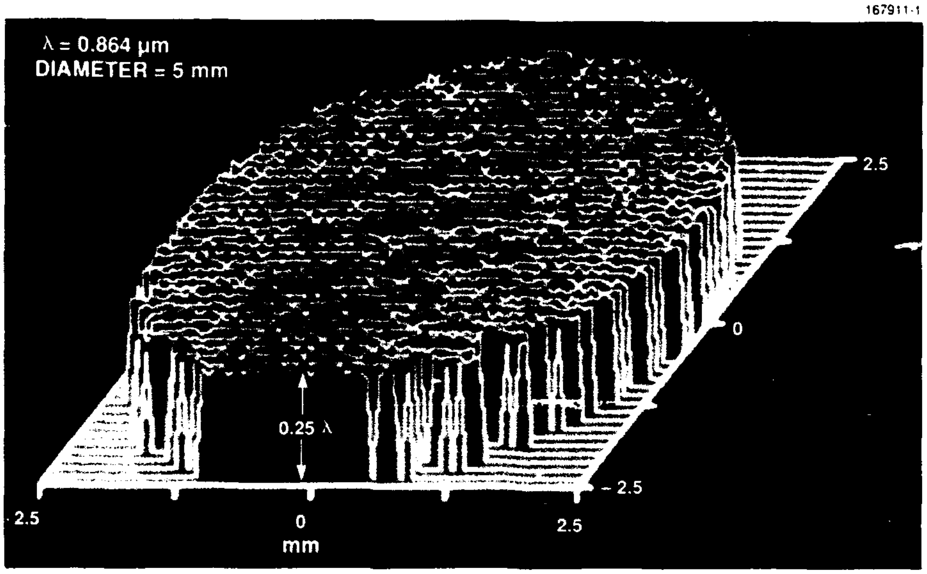

Figure 7. Change in wavefront of source assembly beam after random vibration testing at 15.2 g rms level.

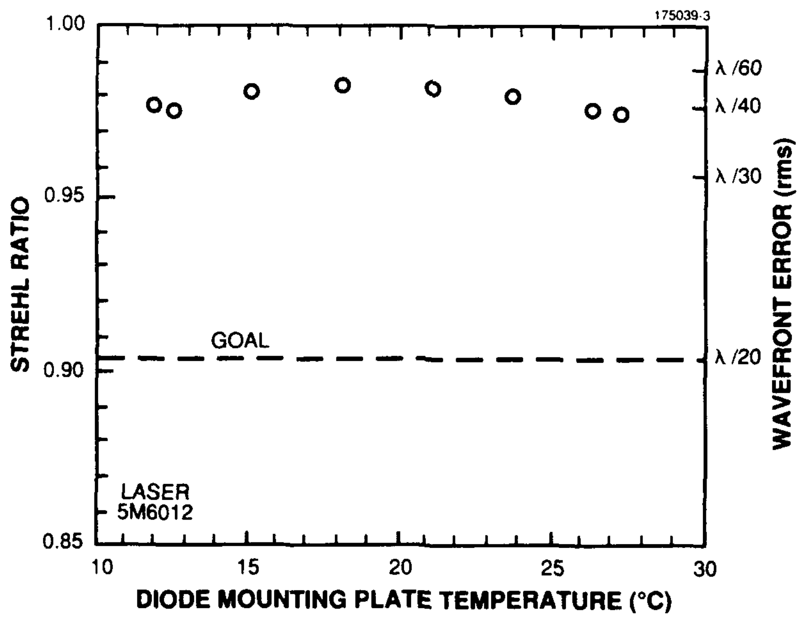

Figure 8. Wavefront error as a function of source assembly temperature.

8. TRANSMITTER QUALIFICATION

Random vibration and thermal cycle testing were performed while the transmitter was mounted to the titanium transmitter mounting plate, which simulated the mounting region on the OMS bench and allowed the mounting technique to be qualified.

Qualification testing of the unpowered transmitter assembly was very similar to that described for the subassemblies. Thermal cycling consisted of six cycles between –30 and 66°C, with a rate of change of 20°C/hr and a dwell time of 1.2 hr at the temperature extremes. Random vibration testing was performed for 2 min in each of three axes, with the spectral content for the x-axis shown in Figure 5. The rms levels were 16.2 g in the x-axis, 8.9 g in the y-axis, and 10.2 g in the z-axis.

The wavefront quality of the transmitter beams was measured using a Ladite interferometer [12] before and after each environmental exposure. The three beams tested maintained a wavefront quality of better than the required $\lambda/20$ rms throughout the testing process. (The wavefront quality of the fourth beam could not be measured due to the laser's multimode operation that was first noted during transmitter alignment. Time constraints prevented the replacement of this source prior to qualification testing.) The average wavefront quality was $\lambda/26$ rms before testing and $\lambda/23$ rms after completing all tests.

Optical power was measured before and after qualification testing, and no degradation was observed. The typical output power level was 26 mW and represented a loss slightly lower than the budgeted 0.9 dB. The low loss can be attributed to the small number of components through which the beam must travel.

The beam position was measured at the source-select-mirror location using a quadrant detector, as described above. The walk of the four beams after the random vibration testing was 30 µm on average [see Figure 9(a)]. The change in beam position after the thermal cycle testing was 20 µm on average [see Figure 9(b)]. The reason for the small shifts cannot be established with certainty; however, since the magnitude and direction of the movements are different for each source, deformation of the support structure is unlikely to have been the cause. We suspect that the beam walk that occurred during random vibration was most likely due to a radial shifting of a lens element in the collimator, while the thermally induced walk was caused by a deformation at the diode-mounting plate interface. Nevertheless, for the largest beam motion the resulting additional loss in the system would be less than 0.1 dB.

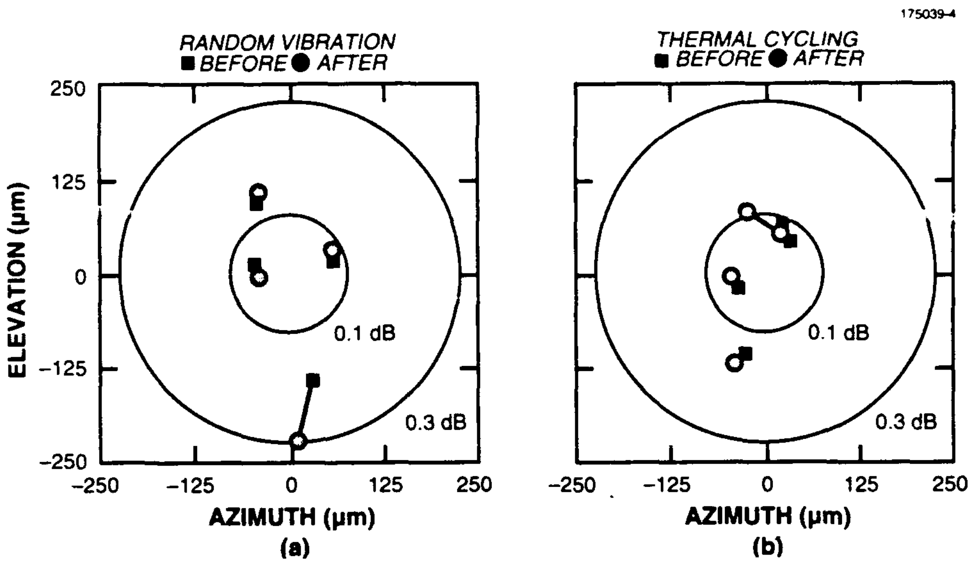

Figure 9. Displacements of beam centers due to (a) random vibration testing, and (b) thermal cycling over the –30 to 66°C range.

9. CONCLUSION

A laser transmitter for space-based heterodyne optical communications has been successfully subjected to a qualification test program that included random vibration exposure at levels up to 16.2 *g* rms for 2 min per axis and repeated thermal cycling from –30 to 66°C. No significant degradation in critical optomechanical characteristics was observed as a result. An average wavefront quality of $\lambda/23$ rms or better was maintained throughout the testing program, and total beam walk was less than 50 μm on average.

The success of the transmitter test program is attributed to several factors. A significant amount of attention was given to the number and types of interfaces between individual components because these are likely failure sites. The supporting structure was made rigid enough to prevent effective coupling with the operating or launch loadings, which, in turn, kept the structural stresses well below microcreep levels. Finally, by rigorously testing individual components and subassemblies the techniques necessary for a successful design were developed early in the design process.

The transmitter is presently being integrated into an engineering model of the OMS for a ground-based demonstration of the critical functions of a space-based laser communications system. This engineering model will include spatial acquisition and tracking routines, boresighting operations, laser-beam diagnostics and control, and 4-ary FSK communications. Testing will measure end-to-end wavefront quality and throughput, beam-tracking performance, and system communications performance.

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A diode-laser transmitter designed for space-based coherent communications has been successfully space qualified. Environmental testing, which consisted of random vibration at levels up to 16.2 *g* rms and thermal cycling over the range of −30 to 66°C, caused no significant degradation in the performance of the transmitter. Principal design issues and the qualification process of subassemblies and the complete transmitter are described.

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